Chapter 2

Magnets

Introduction to Superconductivity

Superconductivity is the phenomenon whereby a metal, alloy, ceramic, etc., when cooled to a low temperature, becomes a perfect conductor of electricity. As the temperature in a metal decreases the electrical resistance decreases until at a certain temperature, known as the critical temperature (T_c), the electrical resistance abruptly drops to zero. Critical temperatures are usually a few degrees above absolute zero. To describe superconductivity fully the concept of current density must be introduced. Current density, J, is the current per unit area carried through a conductor. For example, average house wiring is rated at 10^7 A/m^2, which is also the typical current density of conventional electromagnets with water-cooled copper windings.

Along with the critical temperature, the critical current density (J_c) and the critical magnetic field (B_c) help describe the characteristics of a superconductor. Similar to the phase plots of thermodynamics, the 3D plot of B, T, J shows the critical surface of a material, where superconductivity exists below the surface and normal resistivity everywhere above it. The tests on the superconducting cable for the Tevatron magnets

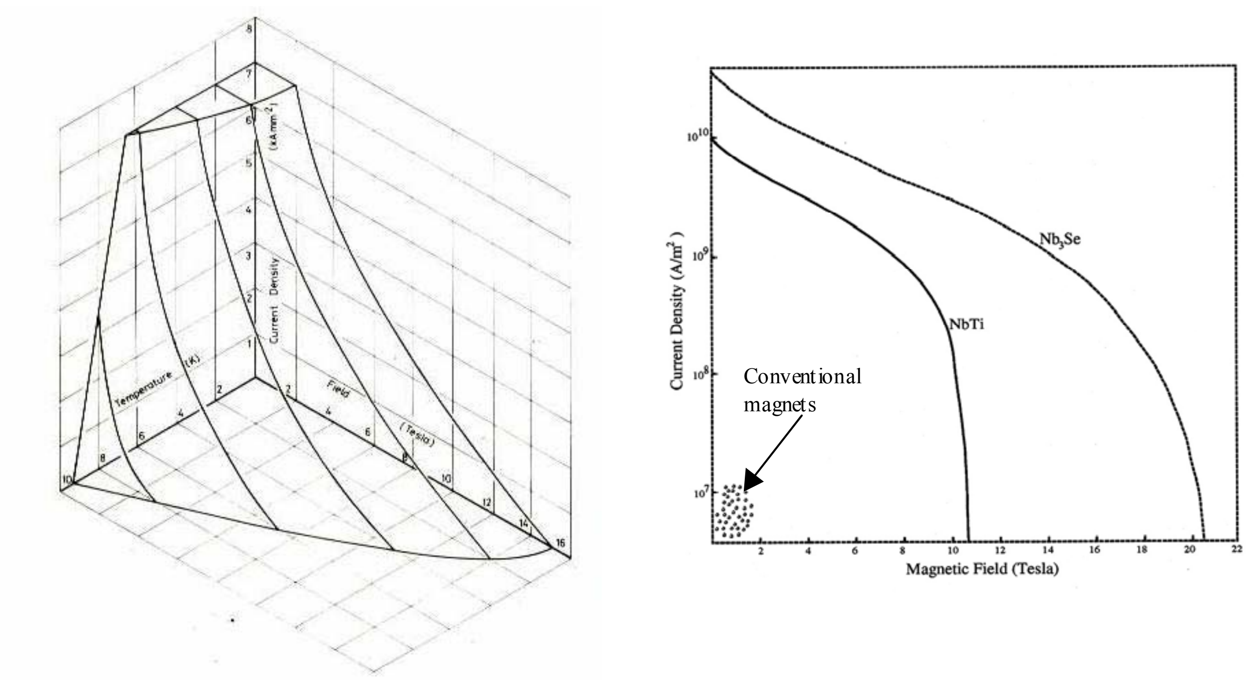


Figure 2.1. The left plot shows the phase plot of NbTi. Below the surface NbTi is superconducting. The right plot is a comparison of 2 superconductors with conventional electromagnets.

gave an average J_c of 1.8×10^9 A/m^2 at 5 T and 4.2 K. At an operating point of 4.6 K, the Magnet Test Facility determined the average magnet current, I_{ave}, in the NbTi superconductor to be 4600 A, or 1.045 TeV.

To keep the NbTi bus at superconducting temperatures magnets must be placed in special helium vessels or cryostats. These are vacuum insulated containers that have an intermediate liquid-cooled nitrogen shield placed between room temperature and the low temperature region.

The NbTi cable has a keystone shape with dimensions 0.044 to 0.055-inch thickness X 0.308-inch width. Twenty-three strands of 0.0268-inch diameter wire are twisted flat to make up the cable. Each strand has 2050 filaments of NbTi alloy in a copper matrix that average 8.7 μm in diameter. The cable is insulated with 1 mil thick double wrapped Kapton and then spirally wrapped in a layer of fiberglass tape.

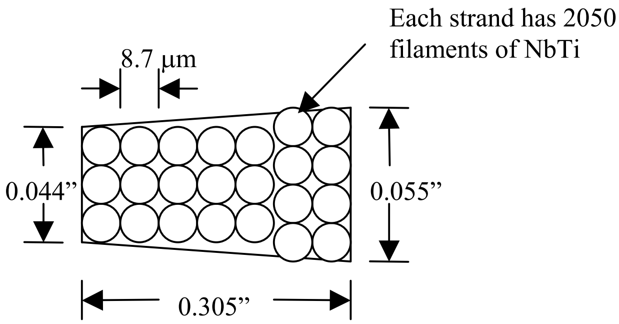


Figure 2.2 A cross section of the NbTi bus.

Dipoles

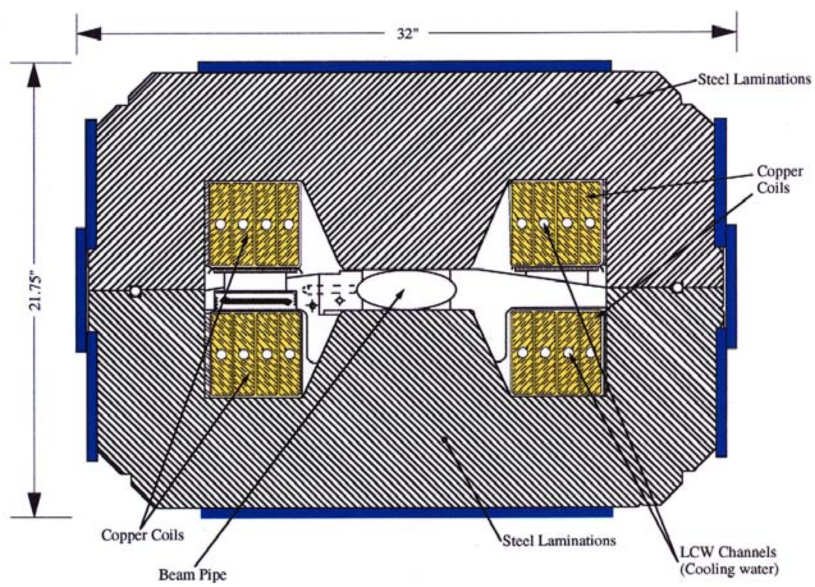


Figure 2.3 Main Injector dipole cross section.

We all know the cross sections of conventional dipoles for the Main Injector, Switchyard, etc. They have 2 sets of coils, top and bottom for a horizontal dipole or left and right for a vertical dipole.

The TeV magnets are much different in the fact that they are cryogenically cooled to become superconducting and have several vacuum chambers within. The center of the magnet contains the beam pipe, which, of course, is under vacuum of the order 10^{-9} torr. Surrounding the beam pipe and following the length of the magnet is single-phase helium at 4.6 K. The single-phase helium keeps the NbTi coil superconducting. Stainless steel collars clamp the magnet coil in place and keep it from distorting during ramping, which can be 4400 amps or more. Around the collared assembly is a two-phase (liquid and gas) helium jacket, which returns the cryogens along the length of the magnet in the opposite direction of the single-phase. This counterflow allows for heat exchanging to occur at the surface of the single-phase tube. Outside of the two-phase jacket are two concentric insulating vacuum spaces. Next is a liquid nitrogen jacket and finally an outer insulating vacuum space, which intercepts heat flow from room temperature. Superinsulation (aluminized Mylar) surrounds the outer insulating vacuum tube as an extra heat radiation shield.

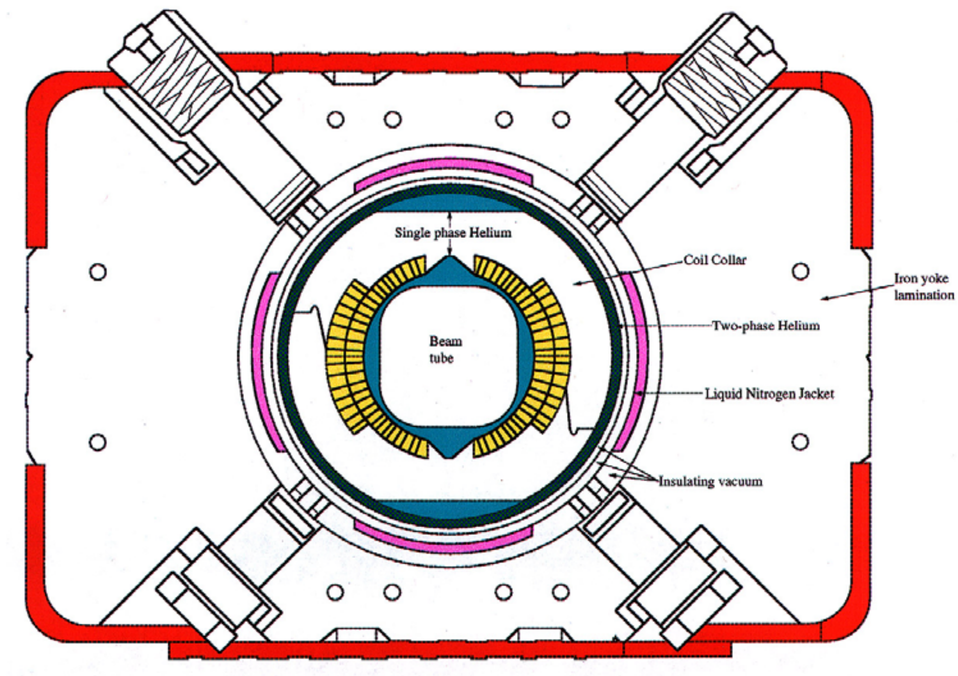


Figure 2.4 Cross section of Tevatron cryogenic dipole.

The entire magnet assembly is vacuum tight. It is held in a laminated iron yolk, which contributes roughly 18% to the total magnetic field. The assembly is precisely adjusted to within 1 mil of center with G10 suspension blocks and preloaded suspension cartridges that allow for thermal contraction and expansion. The 21-foot dipoles have nine sets of suspension points.

As you may have noticed, the coils are not configured like those of the Main Injector dipoles. The conventional dipole coil structure would not produce a uniform dipole field. Instead, the B field would have components in both transverse directions. To produce a perfect dipole field the windings have to take on the shape of two intersecting ellipses.

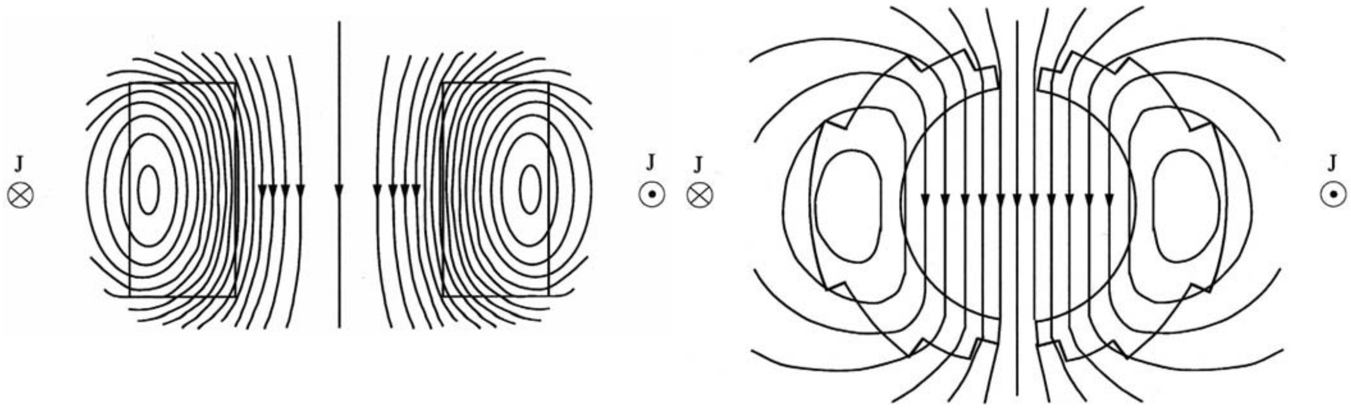


Figure 2.5 The left diagram shows the magnetic field for a normal conductor. The right diagram shows the geometry for the NbTi superconductor that creates the dipole field.

The dipole magnets have a magnetic length of 6.12 m and a total length of 6.40 m. Each magnet produces a deflection angle of 8.1 mrad.

Quadrupoles

Quadrupoles, of course, focus or defocus the beam with respect to the horizontal plane. The geometry for the superconducting quad coils are that of 2 sets of intersecting ellipses rotated 90 degrees apart.

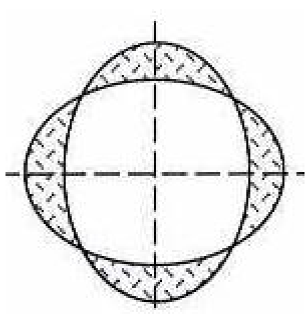


Figure 2.6 Geometry of the superconducting bus that creates the quadrupole field.

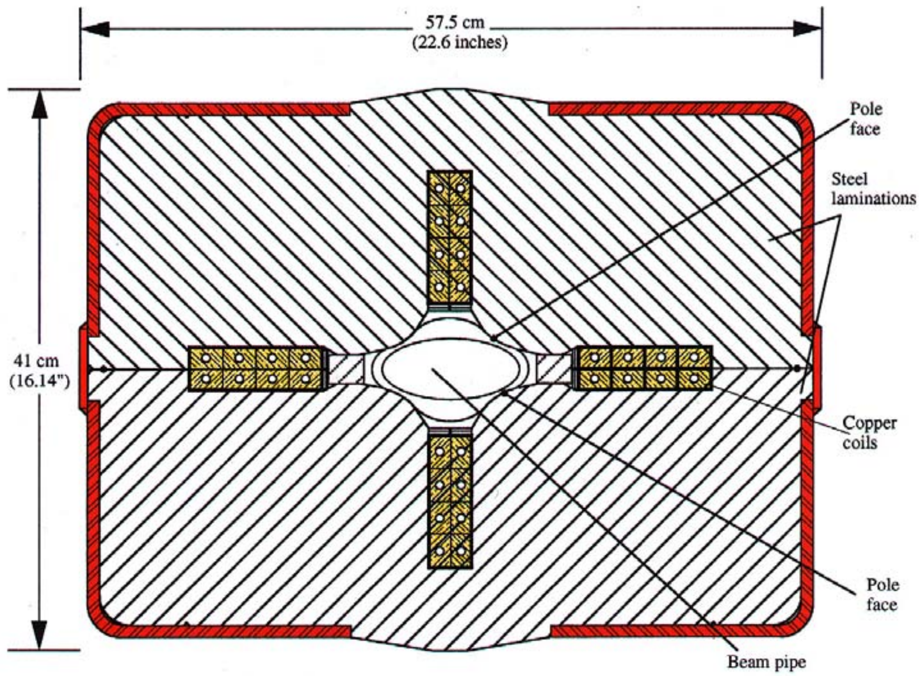


Figure 2.7 Main Injector quadrupole magnet cross section.

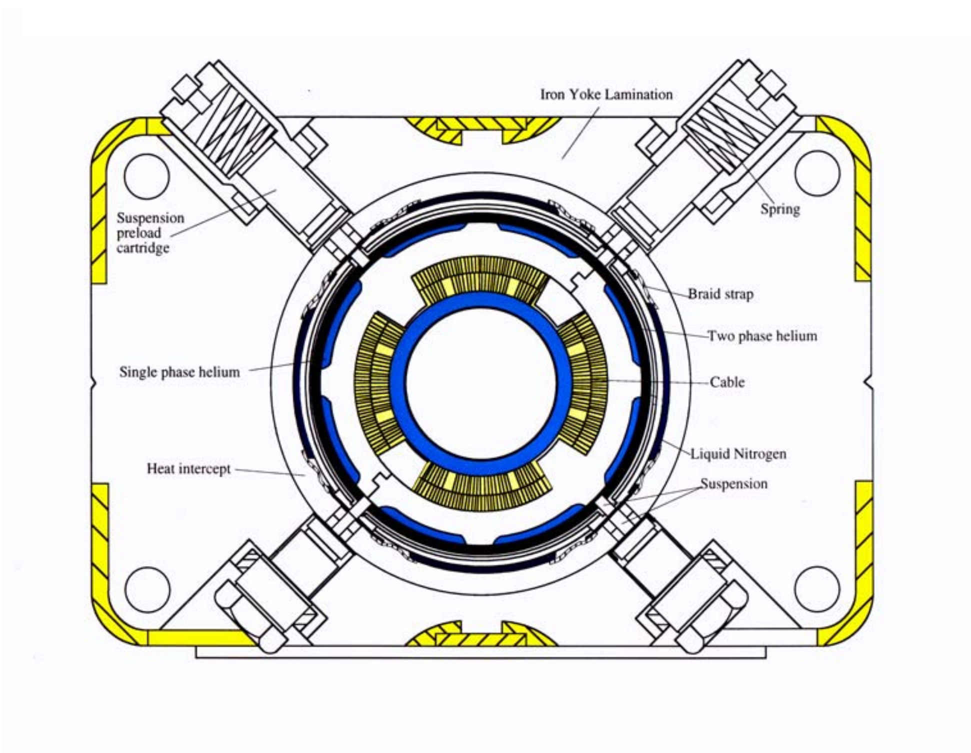


Figure 2.8 Tevatron quadrupole magnet cross section.

Cell and Lattice

As stated in chapter 1, a house consists of a repetitive series of magnets called cells. Houses 1 and 2 have 4 ½ of these repetitive cells and houses 3 and 4 have 4 cells each which yields 17 cells for each sector. Since each sector bends the beam 60 degrees, a cell deflects the beam by 3.5 degrees. Each cell has 10 magnets, 8 dipoles and 2 quads. A cell begins with a quadrupole followed by a mini-straight section, where the correction coil spool piece resides. Next, there are 4 dipoles followed by another quadrupole, correction coil spool piece, and 4 more dipoles. Reference the figure below. This repetitive cycle is broken in 3 places each sector, 0, 17, and 48 locations. The cell described above is one of the repetitive segments of the FODO lattice, that is a focusing quad, 4 dipoles, a defocusing quad, and 4 dipoles.

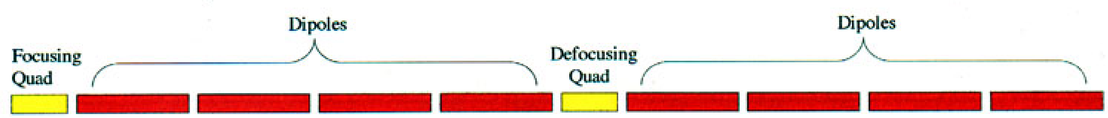


Figure 2.9 The FODO lattice arrangement for the TeV.

Each magnet is a four-pole device, with two leads on each end. The inductance of each magnet is concentrated either on the upper bus (TC type dipole, F quadrupole) or on the lower bus (TB type dipole, D quadrupole). The inductance of a typical "half cell", that is the inductance of either the upper or lower bus through the cell, is about 0.18 H. This yields an inductance for the entire ring of 36 H. The inductive stored energy at 1 TeV (4440 A) is

$$\frac{1}{2}LI^2 = \frac{1}{2}(36H)(4440A)^2 = 3.50x10^8\,Joules.$$

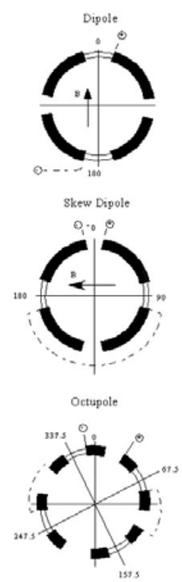
That's right, 350 MJ of energy.

Correction Elements

The previous sections have shown how different magnet design is for the TeV compared to the Main Injector. The same holds true for the correction and adjustment magnets. Two factors were considered in their design and use. First, error fields were no longer just a ramping phenomenon. Inevitable deviations in the superconductor from the ideal configuration produce significant field distortions that are independent of ramping. Therefore, certain corrections are required at all field levels. Second, the beam pipe is relatively inaccessible. It is buried throughout most of the accelerator inside an essentially continuous cryostat. Magnets cannot be added or shifted with ease.

Correction magnets are those required to correct field imperfections and alignment errors of the main quadrupoles and dipoles. Adjustment magnets are those required to tune the optics of the accelerator depending on the operating conditions. Often the same magnet performs both functions. Thus, dipole steering magnets are necessary to compensate for alignment errors so that the beam is in the center of the aperture and also necessary to bump the beam away from a restriction like an injection magnet.

The correction and adjustment magnets are superconducting coils located within the main quadrupole cryostats. They are located immediately downstream of the quadrupole in a spool piece, a stainless steal tube that also houses the main magnet bus, cryogenic flows, and the vacuum connections for the insulation and beam tube vacuum. Most spool pieces contain 2 packages of 3 concentrically wound correctors with 6 pairs of leads coming from cryogenic temperature to room temperature.



There are 26 various configurations of the spool types. The most common will be outlined. The following table will show all of the various packages and spool types. The first corrector package is DSQ I, which contains a horizontal dipole, normal sextupole, and normal quadrupole. The DSQ I is thus used for horizontal steering, chromaticity adjustment, and tune adjustment. The DSQ II package differs in that the dipole is vertical instead of horizontal. The second most common corrector package is the OSQ of which there are 3 varieties, I, II, and III. OSQ I contains an octupole, skew sextupole, and skew quadrupole, whereas OSQ II contains all of the magnets in the normal configuration. OSQ III is different in that only the quadrupole is skewed.

In the table below the various spool types are outlined. The number of poles, P, for each of the 3 coils is given. Thus, a 2P is a dipole, a 4P is a quad, and so on. The S prefix indicates that the coil is skewed. For example, a S-2P is a horizontal dipole rotated 90 degrees, which makes it a vertical dipole.

Spool Type	Upstream Inner Middle Outer	Downstream Inner Middle Outer	Safety Leads	Notes
A	DSQ I 2P 6P 4P	None	No	43” spool length, only one corrector package
B	DSQ II S-2P 6P 4P	None	Yes	43” spool length, only one corrector package
BA	DSQ II S-2P 6P 4P	Bypass	Yes	72” B spool
C	DSQ I 2P 6P 4P	OSQ I 8P S-6P S-4P	No	72” spool
CA	DSQ I 2P 6P 4P	OSQ I 8P S-6P S-4P	Yes	72” spool
CB	DSQ I 2P 6P 4P	None	No	72” spool
D	DSQ II S-2P 6P 4P	OSQ I 8P S-6P S-4P	Yes	72” spool
DA	DSQ II S-2P 6P 4P	None	Yes	72” spool
DR	DSQ II S-2P 6P 4P	OSQ I 8P S-6P S-4P	Yes	72” D spool with recooler for lower temperature
E	DSQ I 2P 6P 4P	OSQ II 8P 6P 4P	No	72” spool
F	DSQ II S-2P 6P 4P	OSQ II 8P 6P 4P	Yes	72” spool
FR	DSQ II S-2P 6P 4P	OSQ II 8P 6P 4P	Yes	72” F spool with recooler for lower temperature
G	DSQ I 2P 6P 4P	OSQ III 8P 6P S-4P	No	72” spool
H	DDQ 2P S-2P S-4P	None	No	5000 A Power Lead 49.91” spool length
HA	DDQ 2P S-2P S-4P	None	No	5000 A Power Lead 49.91” spool length
HH	DDQ 2P S-2P S-4P	None	No	High Temp 5000 A power lead 49.91” spool length
I	30" DD 2P S-2P	Bypass	No	84” spool length
IA	30" DD 2P S-2P	Bypass	No	125” spool length
J	T6 Quad	DSQ I 2P 6P 4P	Yes	5000 A Power Lead Low β quad trim, 72” spool
K	T6 Quad	DSQ II S-2P 6P 4P	Yes	5000 A Power Lead Low β quad trim, 72” spool
L	30" DD 2P S-2P	None	Yes	5000 A Power Lead 56.149” spool length
M	S5 Quad	DSQ I 2P 6P 4P	Yes	2000 A Power Lead Bartelson quad, 72” spool
N	S5 Quad	DSQ II S-2P 6P 4P	Yes	2000 A Power Lead Bartelson quad, 72” spool
P	DDQ 2P S-2P S-4P	None	Yes	5000 A Power Lead 56.149” spool length
R	None Drift Space	None	No	5000 A Power Lead 36” spool length
S	DDQ 2P S-2P S-4P	None	No	49.91” spool length

The table below is the spool map for the Tevatron. It indicates the type of spool located downstream of each main quadrupole.

Quad		Sector					
D	**F**	**A**	**B**	**C**	**D**	**E**	**F**
	11	H	P(B10), R	H	S	H	H
12		D	L	F	L	D	D
	13	C	J	C	J	C	C
14		D	N	F	N	B	D
	15	A	A	A	A	A	A
16		D	N	F	N	D	D
	17	C	M	C	M	C	C
18		DR	DR	F	FR	D	F
	19	C	E	E	C	E	E
21		B	B	B	B	B	B
	22	C	C	G	C	C	G
23		D	F	F	D	F	D
	24	C	E	E	C	E	E
25		B	B	B	B	B	B
	26	C	C	G	C	C	G
27		D	FR	D	DR	FR	F
	28	C	E	E	C	E	E
29		B	B	B	B	B	B
	32	C	C	G	C	C	G
33		D	F	D	D	F	D
	34	C	E	E	C	E	E
35		B	B	B	B	B	B
	36	C	C	G	C	C	G
37		D	F	F	D	F	F
	38	C	E	E	C	C	E
39		B	B	B	B	B	B
	42	C	C	C	C	C	C
43		N	D	N	D	D	D
	44	M	C	M	C	C	C
45		B	B	B	B	B	B
	46	M	C	M	C	C	C
47		K	DR	K	B	FR	FR
	48	L, A, H	A	L, A	A	A	A
49		P	H	S	H	H	H

Figure 2.12 Spool map.

Miscellaneous